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13. ABSTRACT (Maximum 200 words)

The effects of transverse strain on an initially two-dimensional turbulent boundary layer are studied in a direct numerical simulation of a planar channel flow with impulsively started transverse pressure gradient. Consistent with experiments in three-dimensional boundary layers, the simulation shows a decrease in the Reynolds shear stress with increasing transverse strain. Also, the directions of the Reynolds shear stress vector and the mean velocity gradient vector were found to differ. In addition, the simulation shows a drop in the turbulent kinetic energy. Terms in the Reynolds stress transport equations were computed. The balances indicate that the decrease in turbulent kinetic energy is a result of a decrease in turbulence production, along with an increase in turbulent dissipation. The effects of the transverse pressure gradient on the instantaneous flow structures were investigated. (JD)

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Numerical Study of a Three-Dimensional Turbulent Boundary Layer

Final Report

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For the work performed under GRANT AFOSR 87-0285

by

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August 31, 1990

1. Background

This research program was motivated by the curious experimental observations in three-dimensional boundary layers and, in particular, by Bradshaw and Pontikios' (1985) measurements on an infinite swept wing. In these experiments an incoming turbulent flow that is two-dimensional in the mean was subjected to a transverse pressure gradient. The unexpected result was a significant decrease in the magnitude of the Reynolds shear stress. In addition, a lag developed between the angle of the Reynolds shear stress vector and the direction of the mean velocity gradient. None of the existing turbulence models, including those based on the complete transport equations, are capable of predicting these effects. In fact, the predictions for the Reynolds shear stress are in the opposite direction; that is, an increase rather than a decrease with the resulting transverse mean velocity gradient is found. Therefore, turbulence models presently in use do not account for the apparently significant eddy structure changes that take place when a nominally 2-D boundary layer encounters forces in the lateral direction; they simply follow the intuitive reasoning that turbulent stresses ought to increase with increasing mean flow strain rate. Since most practical flows are three-dimensional, improved understanding of the mechanics of three-dimensional boundary layers should have considerable practical utility.

2. Work accomplished to date

This research program on three-dimensional boundary layers has been supported by AFOSR for the period July 1, 1987-June 30, 1990. The objective of this program has been to use the direct numerical simulation technique to study the underlying mechanisms for the behavior of the three-dimensional boundary layers, and to use the results to improve turbulence models. A three-dimensional boundary layer was simulated by a sudden application of a transverse pressure gradient to a fully developed turbulent channel flow (Figure 1). Two cases were calculated: one with transverse pressure gradient, $\frac{\partial p}{\partial z} = 10\frac{\tau_w}{\delta}$, and a second case with a more severe pressure gradient of $100\frac{\tau_w}{\delta}$. The latter simulations were undertaken to enhance the effects seen in the mild pressure gradient case. The computational grid for the first case was with $128 \times 129 \times 128$ mesh points, whereas a grid of $256 \times 129 \times 128$ points was necessary for the high pressure gradient case. Because the transient behavior of the flow is of interest, to obtain a good statistical sample an ensemble of 14 realizations were computed, each starting from different initial fields of fully developed 2-D channel velocity field.

Our study was divided into two parts. The first was to compute all the single point statistical correlations that are relevant to turbulence modeling, including terms in the Reynolds stress budget, and to determine the quantities that have undergone significant changes. The second part was concerned with the examination of the changes to the instantaneous turbulence structures. This portion of the study also involved higher order statistical analysis as well as detailed computer graphics flow visualizations. The results

from the first part are given in the attached manuscript which was recently submitted for publication. Here, we briefly outline the main findings.

2.1 Results on single point turbulence statistics and turbulence modeling

• The main experimental findings were reproduced by the computations. The simulations showed a decrease in the Reynolds shear stress with increasing transverse strain, and the directions of the shear stress vector and the mean velocity gradient vector were found to differ.

• Turbulent kinetic energy, q^2, streamwise, $\overline{u}^2$, and normal, $\overline{v}^2$, components of turbulent intensity, and the structure parameter, $\overline{uv}/q^2$, were found to drop.

• It was determined that the drops were not simply due to flow acceleration caused by the transverse pressure gradient nor due to the change of the appropriate coordinate system as a result of flow turning.

• Analysis of the terms in the Reynolds stress transport equations indicate that the decrease in turbulent kinetic energy is a result of a decrease in turbulence production, which at a later point in the evolution is accompanied with an increase in turbulent dissipation.

• The inter-component transfer mechanism (the pressure strain term in the Reynolds stress equations) is suppressed as a result of the three-dimensional mean flow skewing. This results in the reduction of the normal component of turbulent intensity which leads to a reduction in turbulence production.

• All the effects were enhanced with the higher transverse pressure gradient.

• We have concluded that efforts for improvements in turbulence models capable of predicting 3-D boundary layers should be concentrated on the pressure strain terms and, in particular, on the rapid part of the pressure strain. These models should incorporate an appropriate dependence on the mean flow skewing (see below).

• A new non-linear pressure strain model developed in this study predicts the three-dimensional effects qualitatively but underestimates them.

2.2 Results on the flow structure

The main findings from the second part of this investigation (study of the flow structure) are outlined below:

• Computed **probability density** functions of turbulent intensities show that the reduction in turbulent intensities is largely due to the annihilation of the *most intense* fluctuations (Figure 2). Apparently, the highly intermittent energetic structures have been affected the most. The probability density function of the Reynolds shear stress clearly shows that most of the reduction in turbulent shear stress is caused only by the reduction in the number of energy-producing events (Figure 3). The contributions from the events of quadrants II and IV have been reduced, whereas the (negative) contributions of quadrants I and III have been largely unaffected (Figure 4).

• The root-mean square of the streamwise vorticity increases in the 3-D flow. Its probability density function shows that the increase is from a more frequent number of events with intense positive or negative vorticity at the expense of the events with weak streamwise vorticity. The PDF of the normal component of vorticity shows the opposite effect. Thus, the inclination angle of the intense streamwise vortices may have decreased. A joint probability density function may be necessary to relate the apparent change in the magnitude of the streamwise vortices to their inclination angle.

• The low-speed streaks in the wall layer have weakened, but they remain streaky (Figure 5). The high-speed streaks become wavy in the case of mild transverse pressure gradient, and they rotate and break-up in the case of strong transverse pressure gradient (Figure 6).

• The two-dimensional energy spectrum shows that the small scale structures rotate with the strain (the angle of rotation is the same as that of the velocity gradient vector). However, the large scale structures are more resistant to flow turning and lag the mean velocity gradient vector (Figure 7).

• The energy-producing vortices in the near wall region turn with the velocity gradient vector. Thus, among the three characteristic angles, that of the mean flow, the stress vector, and the mean velocity gradient vector, the latter is dynamically most significant and should be a parameter in turbulence models.

3. Publications

The following journal article has resulted from this work:

Moin, P., Shih, T. H., Driver, D. and Mansour, N. N. Direct numerical simulation of a three-dimensional turbulent boundary layer.

Phys. Fluids A, **2**(10), October 1990.

In addition one Conference paper was presented at the 1989 AIAA Aerospace Sciences Meeting in Reno (*AIAA Paper 89-0373*), and another paper on the structural aspects of

3-D boundary layers will be presented at the Forty-Third Annual Meeting of the Fluid Dynamics Division of APS at Ithaca, NY, Nov. 18-20, 1990.

4. Future Directions

As the results of our study outlined above clearly illustrate, we have gathered numerous facts about three-dimensional boundary layers. Our knowledge of three-dimensional boundary layers has increased significantly; we have gained insight into the modeling aspects as well as the flow structure. However, we have not yet uncovered the physical mechanisms leading to the unexpected behavior of 3-D boundary layers. More study is required on the flow *dynamics* and the temporal evolution of the flow structures. Such a study is the focus of a research program to be sponsored by AFOSR beginning October 1, 1990.

The objective will be to study the evolution of the instantaneous flow structures. Such a task requires extensive computational resources. We have therefore decided to use the minimal flow channel (Jimenez & Moin, 1990) as the basic numerical set-up. This will allow long-term numerical integration of the governing equations with relatively modest computational effort.

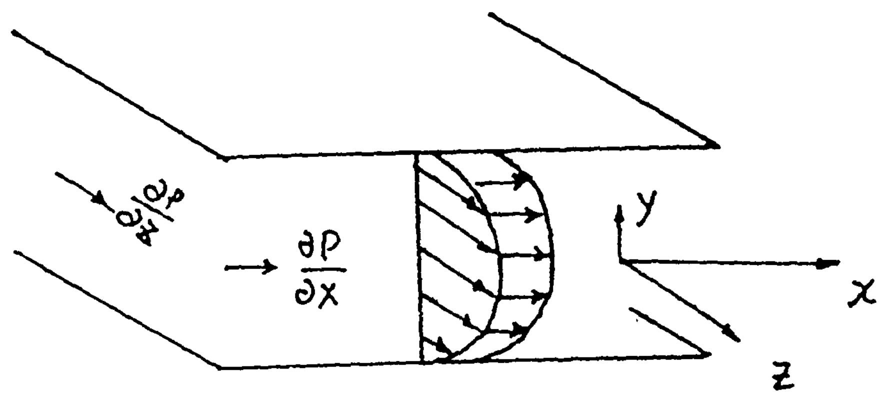


Figure 1. Channel flow with transverse pressure gradient.

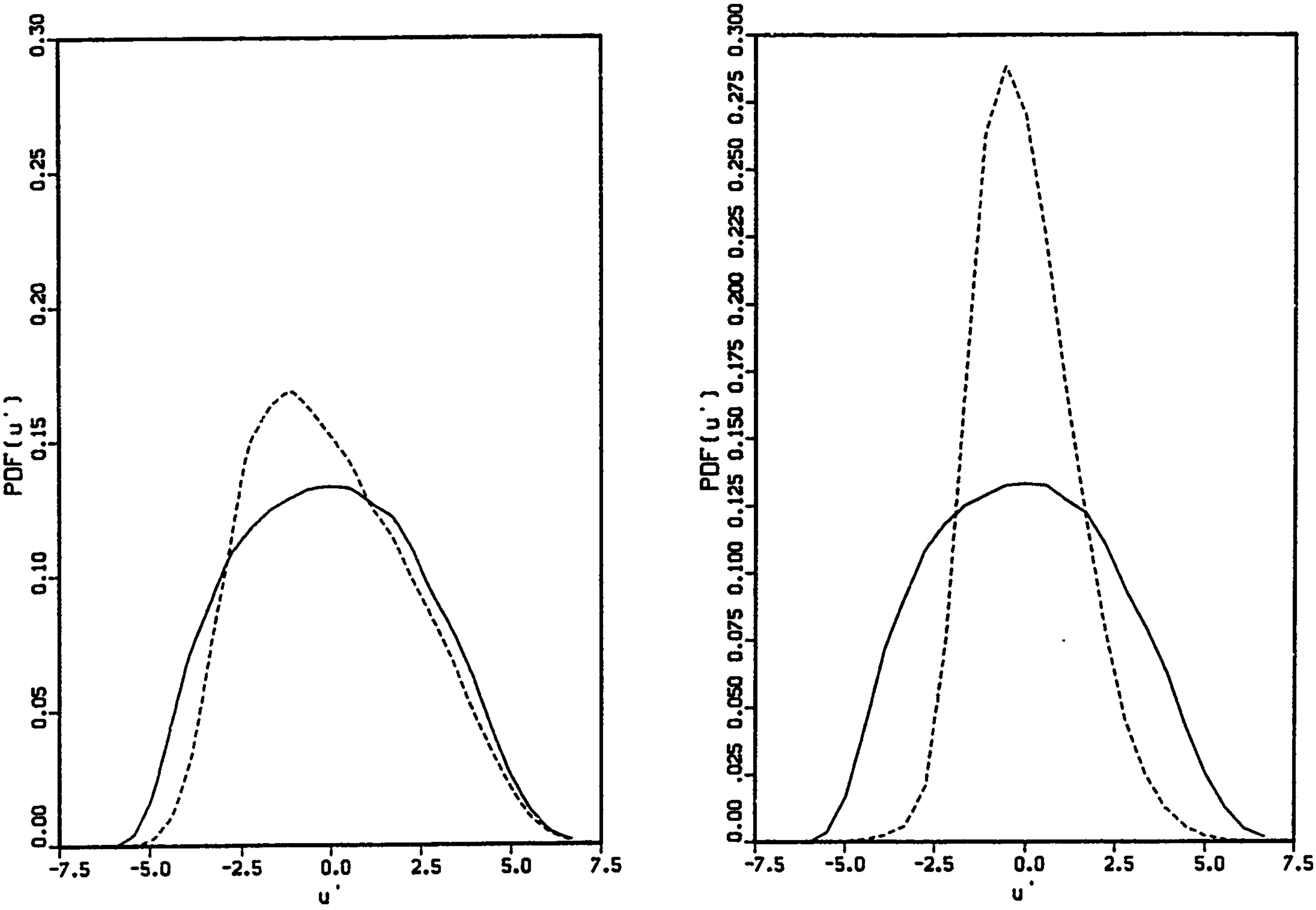


Figure 2. PDF for u' at $y^+ = 10.5$ rotated with the strain angle for mild (a) and strong (b) pressure gradient . 2D flow : ——— , 3D flow: - - - .

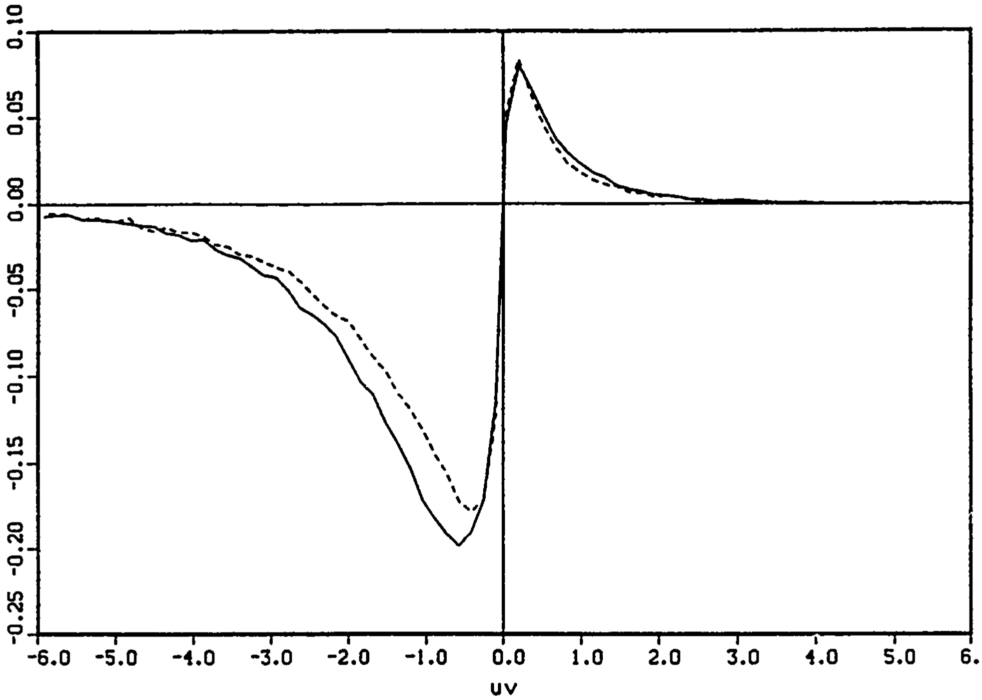


Figure 3. PDF for uv rotated with the strain angle (mild pressure gradient). 2D flow : ——— , 3D flow: ········ .

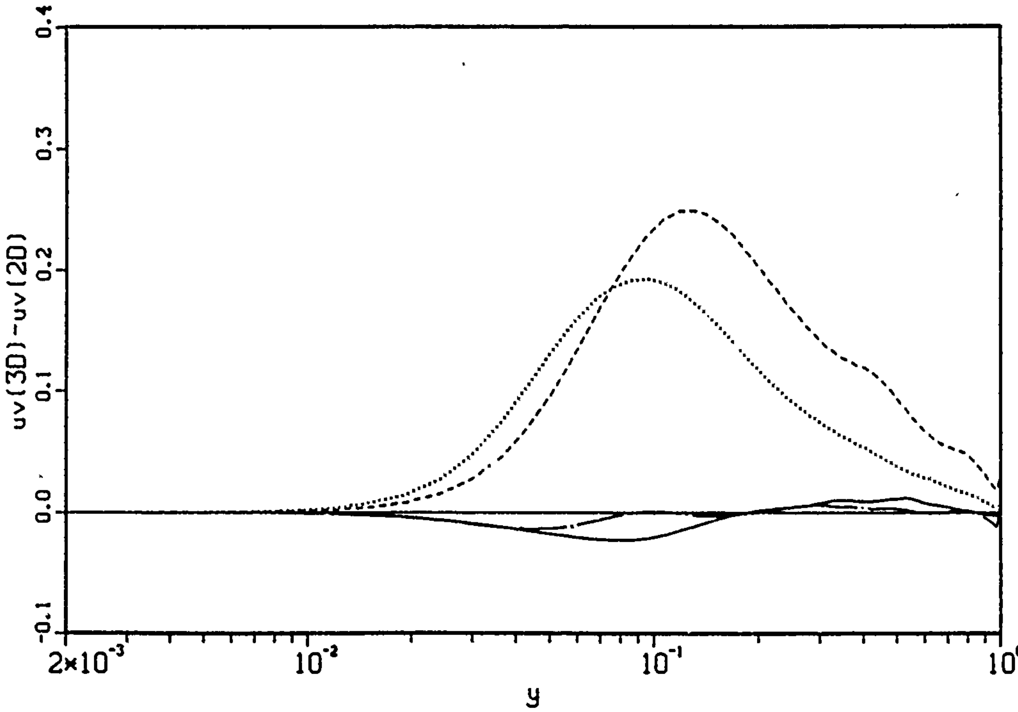
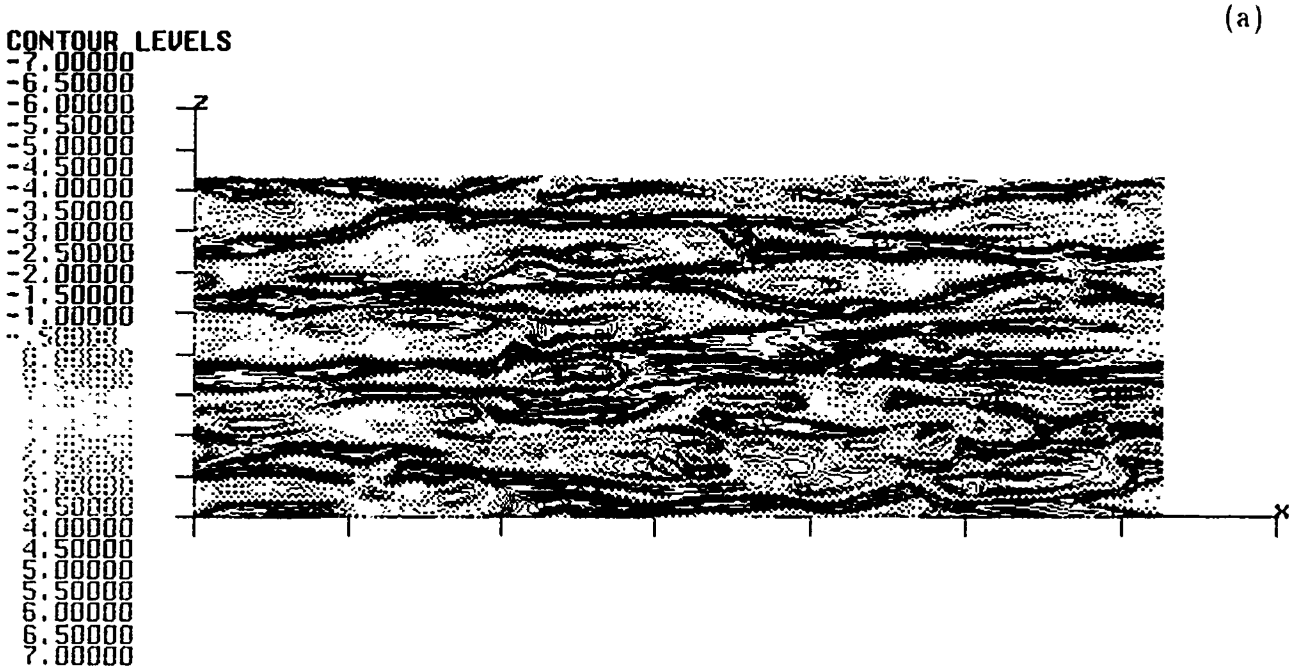


Figure 4. Change in uv in each quadrant (strong pressure gradient).Quadrant 1: ——— , Quadrant 2:- - - - . Quadrant 3 :— — . Quadrant 4 : ········ .



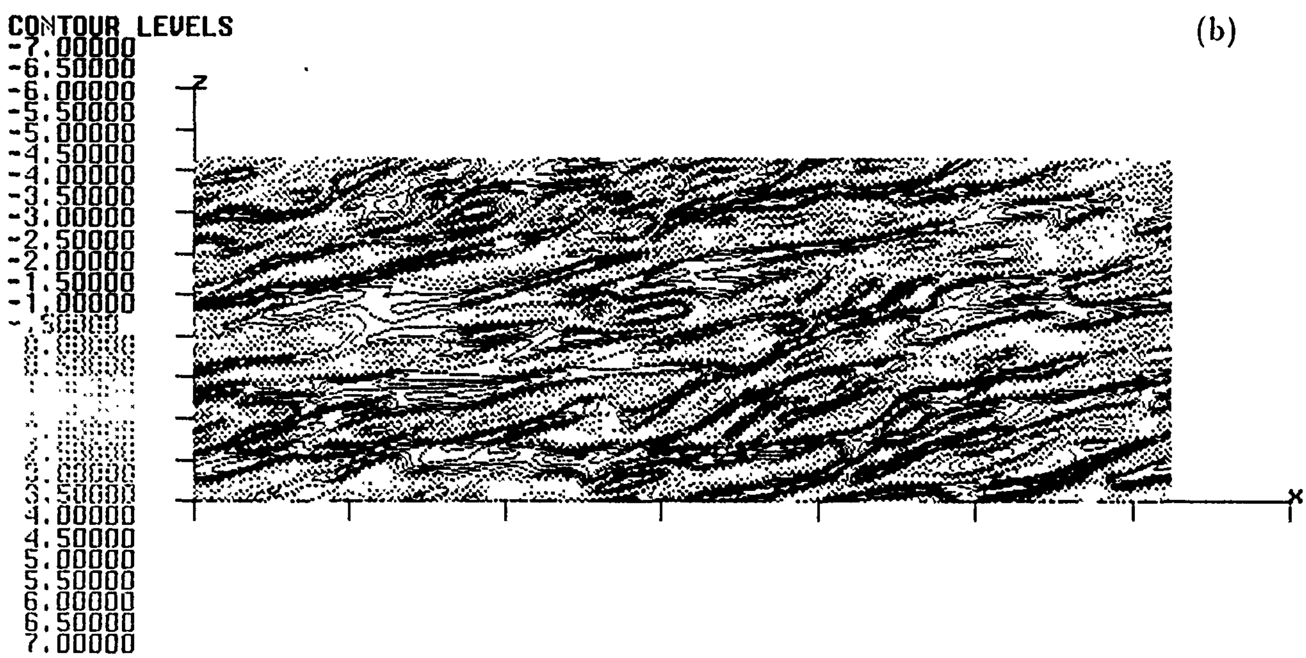


Figure 5. Contours of streamwise velocity fluctuations at $y^+ =$ 10.5 (a) 2D flow (b) 3D flow with mild pressure gradient.

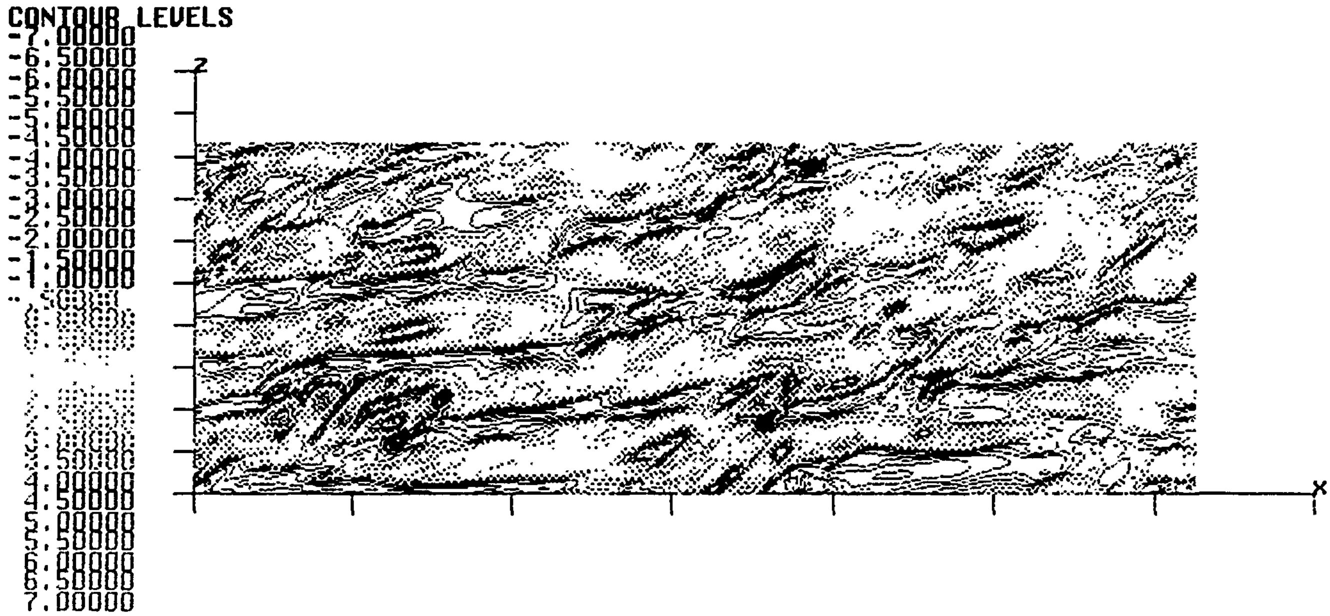


Figure 6. Contours of streamwise velocity fluctuations at $y^+ = 10.5$ (strong pressure gradient).

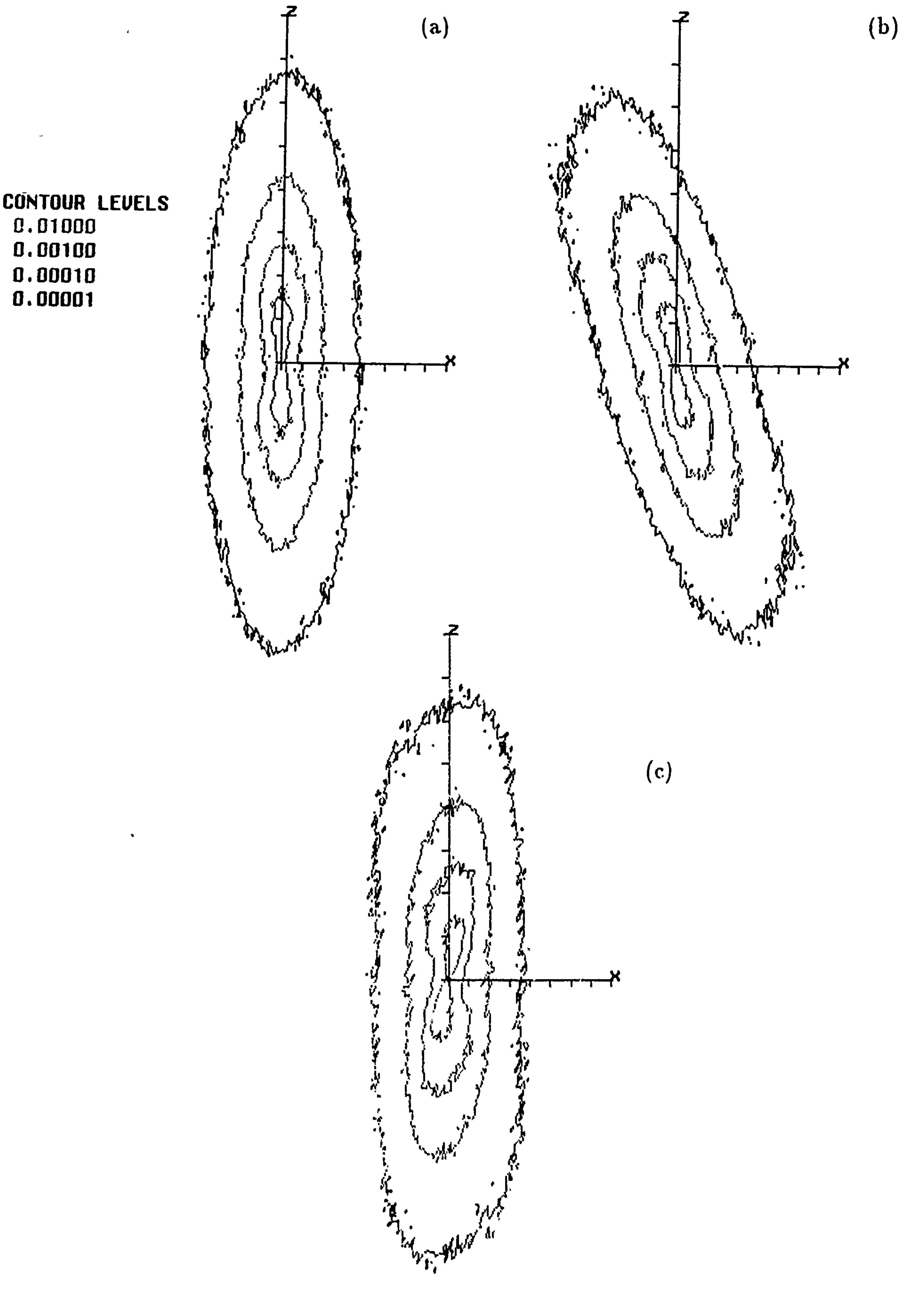


Figure 7. Energy spectrum E_{11} at $y^+ = 10.5$ (mild pressure gradient).(a) 2D flow. (b) 3D flow. (c) 3D flow. E_{11} rotated with the strain angle.